SOLAR COLLECTOR HAVING AN ARRAY OF PHOTOVOLTAIC CELLS ORIENTED TO RECEIVE REFLECTED LIGHT

CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of Application Serial No. 10/241,806, filed September 10, 2002, and entitled *Solar Cell Having a Three-Dimensional Array of Photovoltaic Cells Enclosed Within an Enclosure Having Reflective Surfaces*, which is a continuation-in-part of Application Serial No. 09/953,501, filed September 11, 2001, and entitled *Solar Cell Having a Three-Dimensional Array of Photovoltaic Cells Enclosed Within an Enclosure Having Reflective Surfaces*, now United States Patent No. 6,515,217, both of which are incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

The present invention relates generally to solar collectors, and more particularly to a solar collector having a three-dimensional array of substrates oriented at angles relative to each other and to light received on the solar collector to provide improved efficiency, extended operating life and reduced manufacturing cost.

BACKGROUND OF THE INVENTION

Solar or photovoltaic cells (PVCs) are semiconductor devices having P-N junctions which directly convert radiant energy of sunlight into electrical energy. Conversion of sunlight into electrical energy involves three major processes: absorption of sunlight into the semiconductor material; generation and separation of positive and negative charges creating a voltage in the PVC; and collection and transfer of the electrical charges through terminal connected to the semiconductor material. PVCs are widely known and commonly used in a variety applications, including providing electrical energy for satellites and other space craft, marine vessels, installations in areas not served by a grid of an electric utility company, and

portable consumer electronics devices such as radios, tape/compact disc players and calculators.

Heretofore PVCs have not been widely used as a main or even auxiliary source of power for residences and businesses having access to conventional power sources, for example, through a power grid of an electric utility company. There are several reasons for this, the most important of which is cost. Electricity produced from solar cells tends to be relatively expensive compared to that available from conventional power sources such as hydroelectric, oil-fired, coal fired and nuclear power plants.

Although the cost of installing, maintaining and repairing solar electric generation arrays or systems is not insignificant, the greatest cost associated with solar energy is the cost of the manufacturing the PVCs. Referring to FIG. 1, prior art PVCs 20 are typically formed on an ultra-pure silicon wafer or substrate 22 containing materials such as Indium Phosphide, Gallium Arsenide, Germanium, and related materials, which in itself can cost from about 300 hundred to about 5 thousand dollars apiece depending on size. For example, an 8 inch diameter silicon commonly used in manufacturing PVCs typically costs about 2.5 thousand dollars. Furthermore, traditionally a large number of individual PVCs 20 were fabricated on a single substrate 22 by (i) depositing or growing a doped layer of semiconductor material, such as silicon, over the substrate 22 including a dopant of an opposite type; (ii) patterning and etching the substrate 22 with the doped layer thereon to form individual PVCs 20; (iii) depositing a metal layer over the etched substrate 22; (iv) patterning and etching the metal layer to form vias, contacts and lines interconnecting the individual PVCs 20; and (v) inspecting and testing the finished PVCs 20 to remove from an output circuit defective PVCs. The time, equipment and skilled operators required to perform each of the above steps makes the cost of solar electricity extremely expensive, and impractical for just about any use for which an alternative conventional energy source is available.

In an effort to reduce costs, some of the latest generations of PVCs have been monolithic PVCs in which substantially the entire surface of a substrate is taken up a by single large PVC, thereby eliminating much of the time and costs associated with patterning and etching the doped layer and the metal layer. However, this approach has not been wholly successful, since unlike with a substrate having numerous individual PVCs which can be individually removed

from the output circuit, a single defect at any point in the monolithic PVC would render the entire substrate useless. In practice, this has resulted in yields well below 40%, offsetting or completely negating any cost savings realized with this approach.

Yet another problem with prior art PVCs is their low external quantum efficiency. By external quantum efficiency it is meant the proportion of the available photons converted into electrical energy. Power from the sun arrives at Earth in the form of photons of light in a wide spectrum from approximately 120 nanometers to 20 micrometers. The total solar irradiance, neglecting absorption in the atmosphere, is approximately 135 mW/cm^2 (about 10,000 watts per square meter). Thus, a significant amount of solar radiation is available, but is not absorbed by today's commercially available PVCs. The challenge to photovoltaic manufacturers has always been how to convert this abundance of energy into electricity.

Inefficiency in converting available light into electrical energy is particularly a problem for solar electric systems having limited power generating capability. This is because usable solar energy is available for only a fraction of a day, when it is available the PVCs must generate energy to meet current demands and generate sufficient energy to be stored for use when usable solar energy is unavailable. Thus, conventional solar electric systems must either have relatively large numbers of PVCs, which as explained above are costly, or have a high degree of efficiency. Unfortunately, prior art PVCs are often only from about 15 to 19% efficient, and more typically from about 10 to 14% efficient.

Referring to FIG. 2 it is seen that a major reason for this poor efficiency of conventional solar collectors comes from the reflectance of photons from front and buried surfaces of PVCs having substantially flat surfaces.. External Quantum Efficiency is reduced by the reflected photons, which either never enter the cell (front surface reflection) or are reflected from the back surface or metallization layer interfaces and exit the cell without being absorbed. Thus, a significant or even a large proportion of the light incident on a surface 24 of the PVC 20 is simply reflected away again.

Some attempt has been made to overcome these problems through the addition of anti-reflective coatings to or treatment of the surface of the PVCs to reduce reflection. For example, U.S. Patents Nos. 5,080,725, and 5,081,049, describe methods of manufacturing PVCs in which the surface of the PVCs are textured or contoured to form features such as ridges, pyramids and grooves which minimize surface reflection from the PVCs and maximizes reflection of light from internal surfaces thereby trapping light within the PVC and increasing the chances of light being absorbed.

While an improvement over the prior art these shaping approaches have not been wholly satisfactory for a number of reasons. Fundamentally, although the reflection of light from the surface of the PVCs is reduced it is not eliminated and anti-reflective coatings or surface treatments do nothing provide for the re-absorption of reflected light through secondary or higher order reflections. Moreover, the addition of anti-reflective coatings or contouring of the PVCs adds to the cost of the manufacturing the PVCs making the already high cost of solar electricity prohibitively expensive, and impractical for just about any use for which an alternative conventional energy source is available.

A more fundamental problem is due to quantum mechanical properties of the semiconductor crystal of the PVCs. Conventional PVCs are capable of utilizing or converting into electricity only a narrow range of light wavelengths corresponding to a band-gap energy of the p-n junction of the PVC, no matter how much light is concentrated or incident thereon. For example, although solar radiation includes wavelengths from 2x10-7 to 4x10-6 meters, silicon based PVCs having a band gap energy of about 1.1 electron volts (eV) are capable of utilizing only wavelengths from about 0.3 x 10-6 to about 3.0 x 10-6 meters. Similarly, gallium-arsenide

(GaAs) based PVCs, aluminum-gallium-arsenide (AlGaAs) based PVCs, and germanium (Ge) based PVCs have band gap energies of 1.43, 1.7 and 0.5 eV respectively, and are therefore sensitive to other wavelengths.

Accordingly, there is a need for a solar collector that is inexpensive to fabricate, highly efficient in its utilization of available solar radiation, and which has an extended operational life.

The present invention provides a solution to these and other problems, and offers other advantages over the prior art.

SUMMARY

It is an object of the present invention to provide a solar collector having an array of photovoltaic cells with improved efficiency, extended operating life and reduced manufacturing cost.

According to one aspect of the present invention, the solar collector includes a number of substrates arranged in a two-dimensional array of, each substrate having a monolithic photovoltaic cell (PVC) formed on a surface thereof for converting light incident thereon into electrical energy. The PVCs may include at least two different types of PVCs receptive to different wavelengths of light and having different band gap energies. The array of substrates are enclosed within an enclosure having a top-wall with an anti-reflective coating through which light is passed to the PVCs, and bottom and sidewalls having reflective coatings to reflect at least a portion of light incident thereon onto the PVCs. Preferably, the enclosure further includes end-walls joining the top and bottom walls. Like the top-wall, the end-walls also have anti-reflective coatings thereon and join the top-wall at an angle

selected to facilitate passage of light to the PVCs from a light source inclined relative to a surface of the top-wall.

In one embodiment, the PVCs include at least two different types of PVCs selected from a group consisting of silicon based PVCs, gallium-arsenide (GaAs) based PVCs, aluminum-gallium-arsenide (AlGaAs) based PVCs, and germanium (Ge) based PVCs. Preferably, where the PVCs include GaAs, AlGaAs or Ge based PVCs, the PVCs include a top passivation layer to filter damaging radiation.

In another embodiment, the solar collector further includes a voltage output circuit or circuit electrically coupling all the PVCs to a single voltage output from the solar collector. Generally, the circuit has a number of voltage converters to match voltages from the different types of PVCs to a common output voltage. The circuit can couple the PVCs in parallel, in series or in a combination of both. In one alternative embodiment, a number of a particular type of PVCs may be connected in series with one another and in parallel with a second number of a second type of PVCs having a different band gap energy to provide a common output voltage. For example, the solar collector can include 15 AlGaAs based PVCs having a band gap energy of 1.7 electron volts (eV), 18 GaAs based PVCs having a band gap energy of 1.4 eV, and 23 silicon based PVCs having a band gap energy of 1.1 eV to provide a common output voltage of about 25 volts direct current (vdc).

In another aspect the present invention is directed to a solar collector having a number of substrates arranged a three-dimensional array. Each substrate has at least one PVC formed on a surface thereof for converting light incident thereon into electrical energy. The three-dimensional array includes a lower or base-layer of substrates, and at least one elevated-tier of substrates positioned above and separated from the base-layer of substrates, so that at least a portion of the light passes

between the substrates of the elevated-tier and is absorbed by the substrates of the base-layer.

In one embodiment, the elevated-tier includes substrates having surfaces with the PVCs formed thereon oriented to receive at least some of the light reflected from the substrates of the base-layer. Preferably, the PVCs are monolithic PVCs, and include at least two different types of monolithic PVCs selected from a group consisting of silicon, GaAs, AlGaAs, and Ge based PVCs. More preferably, the where the PVCs include GaAs, AlGaAs or Ge based PVCs, these PVCs are oriented to receive only light reflected from the substrates of the base-layer, thereby reducing their exposure to damaging levels of short wavelength or ultraviolet radiation. Optionally, the GaAs, AlGaAs and Ge based PVCs include a top passivation layer to filter-out or further reduce their exposure to damaging radiation.

In yet another aspect the present invention is directed to a solar collector including a three-dimensional array of substrates enclosed within an enclosure having a top-wall with an anti-reflective coating through which light is passed to the PVCs, and bottom and sidewalls having reflective coatings to reflect at least a portion of light incident thereon onto the PVCs. As above, each substrate has a PVC formed on a surface thereof, and the three-dimensional array includes a base-layer of substrates, and at least one elevated-tier of substrates positioned above and separated from the base-layer of substrates, so that at least a portion of the light passes between the substrates of the elevated-tier and is absorbed by the substrates of the base-layer.

In a preferred embodiment, the enclosure further includes end-walls joining the top and bottom walls, and the substrates of the elevated-tier are electrically coupled to and supported above the base-layer by a ground conductor affixed at both

ends thereof to either the end-walls or the sidewalls of the enclosure. The ground conductor can include one or more wires or straps, or a stamped or extruded aluminum or similar metal carrier. Optionally, the substrates of the elevated-tier can be further supported by voltage conductors affixed the substrates and to the enclosure.

In one embodiment, the elevated-tier includes substrates having surfaces with the PVCs formed thereon oriented to receive at least a portion of light reflected from the substrates of the base-layer and/or from the bottom-wall of the enclosure. It will be understood that the solar collector can include multiple elevated-tiers, each having substrates on a top portion thereof and on a bottom portion thereof. The substrates on the top portion are oriented to receive light directly through the top-wall of the enclosure and light reflected from substrates on the bottom portion of an overlying tier. The substrates on the bottom portion of the elevated-tiers are oriented to receive light reflected from either substrates on the top portion of an underlying tier, the bottom layer of substrates, or the sidewalls and bottom-wall of the enclosure. Preferably, the elevated-tiers are offset from one another such that at some portion of the substrates of each elevated-tier and the bottom layer receive at least some light passed directly through the enclosure and onto the substrates.

In another embodiment, the PVCs include at least two different types of monolithic PVCs selected from a group consisting of silicon, GaAs, AlGaAs, and Ge based PVCs. Where the PVCs include GaAs, AlGaAs or Ge based PVCs, these PVCs are oriented to receive only light reflected from the substrates of the base-layer, thereby reducing their exposure to damaging levels of short wavelength or ultraviolet radiation. Optionally, the GaAs, AlGaAs and Ge based PVCs include a top passivation layer to filter-out or further reduce damaging radiation.

Generally, the solar collector further includes a circuit electrically coupling the PVCs to a voltage output from the solar collector, the circuit including a number of voltage converters to match voltages from the different types of PVCs to a common output voltage.

In yet another embodiment, the solar collector further includes a cooling mechanism selected from the group consisting of: (i) a number of vents in the enclosure to enable movement of air therethrough; (ii) vents in the enclosure and a fan to facilitate movement of air through the enclosure, the fan powered by at least a part of the voltage output from the PVCs; and (iii) a heat exchanger thermally coupled to at least some of the substrates and/or the enclosure, the heat exchanger including one or more passages or tubes through which a fluid is passed to cool the solar collector. In one preferred version of this embodiment, the heat exchanger is adapted to provide heat or heated water, in particular potable water, to a residence or business.

In still another aspect the present invention is directed to a solar collector including a three-dimensional array of substrates each having a photovoltaic cell (PVC) formed on a surface thereof for converting light incident thereon into electrical energy. Generally, the three-dimensional array includes a base-layer of substrates, and a first elevated-tier of substrates positioned above and separated from the base-layer of substrates, and the surfaces of the base-layer of substrates are oriented at an angle relative to the light incident thereon to reflect light received thereon to the substrates of the first elevated-tier of substrates. Preferably, the surface of a first substrate of the first elevated-tier of substrates is oriented at an acute angle relative to the surfaces of the base-layer of substrates to receive light reflected from the substrates of the base-layer, and to reflect light onto the surface of

a second substrate of the first elevated-tier of substrates. Alternatively, a first substrate of the first elevated-tier of substrates is oriented to reflect light received from the substrates of the base-layer onto the surface of a substrate in a second elevated-tier of substrates positioned above and separated from the first elevated-tier of substrates.

In another aspect the present invention is directed to a solar collector having an enclosure enclosing an array of substrates, each substrate having a monolithic PVC formed on a surface thereof for converting light incident thereon into electrical energy, the enclosure including a top-wall with a concentrator through which light is passed to a base-layer of substrates.

According to another aspect of the present invention, the solar collector has an array of substrates with photovoltaic cells, the substrates oriented at angles relative to each other such that light reflected from a first substrate is reflected onto the surface of a second substrate, thereby improving efficiency and reducing manufacturing cost.

In one embodiment, the solar collector includes an array of a number of substrates, each substrate having a photovoltaic cell (PVC) formed on a first or top surface thereof, the array including at least a first substrate and a second substrate. The first surfaces of the first and second substrates are oriented at an angle relative to each other, and to a direction of propagation of light received on the first surface of the first substrate such that at least a portion of light reflected from the first substrate is reflected onto the first surface of the second substrate, thereby increasing efficiency of the solar collector. Generally, the substrates further include second or lower surfaces, and the first surface of each of the substrates is substantially planar and substantially parallel to the second surface. In accordance with the present

invention, the first surface of each of the substrates is substantially absent an anti-reflective coating.

The efficiency of the solar collector varies inversely with the angle between the first surfaces of the first and second substrates for angles between 140° and a predetermined minimum angle. Preferably, the predetermined minimum angle is greater than or equal to 20°.

The PVCs formed on the first surfaces of the substrates can include either or both monolithic PVCs and multiple-junction PVCs. Generally, the PVCs are selected from the group consisting of Silicon based PVCs, Gallium-Arsenide (GaAs) based PVCs, Aluminum-Gallium-Arsenide (AlGaAs) based PVCs, Germanium (Ge) based PVCs, and Gallium Indium-Phosphide (GaInP) based PVCs.

Optionally, the array of substrates is enclosed within an enclosure having a top-wall through which light is passed to the PVCs a bottom wall and side walls. Preferably, the inner surfaces of all the walls are reflective surfaces. The reflective surfaces of the inner walls reflect at least a portion of light incident thereon onto the first surfaces of the substrates.

In another embodiment, the array further includes at least a third substrate, and the first surfaces of the first, second and third substrates are oriented at angles relative to each other and to a direction of propagation of light incident on the solar collector, such that light reflected from the first substrate is reflected onto the first surfaces of at least one of the second and third substrates. Generally, each of the first, second and third substrates comprise an edge proximal to an edge of at least one other substrate, and the first surfaces of the substrates are shaped and oriented relative to one another to form part of a concave inner surface of a polyhedron or geometric figure defined by three or more planar sides.

In one version of this embodiment, the first surfaces of the first, second and third substrates form part of first, second and third inner surfaces of an inverted three sided pyramid. Preferably, each of the first, second and third inner substrates are shaped and sized to form first, second and third isosceles triangles.

In yet another embodiment, the array further includes a fourth substrate having a PVC formed on the first surface thereof, and the first surfaces of the first, second, third and fourth substrates are oriented at angles relative to each other and to a direction of propagation of light incident on the first surface of the first substrate such that light reflected from the first substrate is reflected onto the first surface of the fourth substrate. Preferably, the first surfaces of the second, third and fourth substrates are also oriented to receive light thereon. More preferably, the second, third and fourth substrates are oriented such that light reflected from the second substrate is reflected onto at least one of the first surfaces of the first, third and fourth substrates. Light reflected from the third substrate is reflected onto at least one of the first surfaces of the first, second and fourth substrates. Light reflected from the fourth substrate is reflected onto at least one of the first surfaces of the first, second and third substrates.

In one version of this embodiment, the first surfaces of the first, second, third and fourth substrates form part of first, second, third and fourth inner surfaces of an inverted four sided pyramid. Preferably, each of the first, second, third and fourth inner substrates are shaped to form first, second, third and fourth isosceles triangles.

In still another embodiment, the solar collector further includes a plurality of substrates oriented at an angle relative to each other, and an enclosure enclosing the array of substrates, the enclosure including a top-wall with a concentrator through

which light is passed to at least the first substrate. Preferably, the concentrator is a non-imaging concentrator that diffusely focuses light on the first substrate.

Advantages of the solar collector of the present invention include any one or all of the following:

(i) an improved efficiency of up to 3 times that of similarly sized conventional solar collectors;

(ii) reduced size or 'footprint' as compared to conventional solar collectors with a similar power output, thereby simplifying an installation process and enabling use of the inventive solar collector in locations having a limited area available for a solar cell;

(iii) extended operating life made possible by reducing exposure of sensitive PVCs to damaging levels of short wavelength or ultraviolet radiation, and by actively cooling the solar collector to maintain the PVCs below a maximum desirable operating temperature;

(iv) ability to use fluid from a heat exchanger used to cool the solar collector to provide heat or heated water to a residence or business;

(v) reduced manufacturing or fabrication cost made possible by use of monolithic PVCs thereby eliminating the need to form and interconnect multiple PVCs on a single substrate; and

(vi) reduced manufacturing time achieved by eliminating the need to form and interconnect multiple PVCs on a single substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

These and various other features and advantages of the present invention will be apparent upon reading of the following detailed description in conjunction with the accompanying drawings, where:

FIG. 1 (Prior Art) is a plan view of a substrate having a plurality of individual photovoltaic cells (PVCs) formed on a surface thereof;

FIG. 2 (Prior Art) is a simplified block diagram of a typical solar cell showing incident light striking active devices on a top surface of the solar cell;

FIG. 3A is a plan view of a solar collector with a plurality of substrates, each with a PVC formed thereon, enclosed within a reflective enclosure and arranged in a three-dimensional array having a single elevated-tier of substrates according to an embodiment of the present invention;

FIG. 3B is a side view of the solar collector of FIG. 3A showing the position of the substrates of the elevated-tier relative to a base-layer, and the reflection of light among the plurality of substrates according to an embodiment of the present invention;

FIG. 4A is a perspective view of a solar collector with a plurality of substrates, each with a PVC formed thereon, enclosed within a reflective enclosure and arranged in a three-dimensional array having multiple elevated-tier of substrates according to an embodiment of the present invention;

FIG. 4B is a side view of the solar collector of FIG. 4A showing the position of the substrates of the elevated-tiers relative to a base-layer, and the reflection of light among the plurality of substrates according to an embodiment of the present invention;

FIG. 5 is a top view of an elevated-tier of substrates in a solar collector showing use of a common ground wire(s) to support and interconnect the substrates of the elevated-tier according to an embodiment of the present invention;

FIG. 6 is a partial perspective view of an enclosure showing an attachment of ground wires supporting elevated-tiers to the enclosure according to an embodiment of the present invention;

FIG. 7 is a partial top view of a bottom layer of PVCs showing orientation of wafers or substrates within a row and interconnection of a common ground wire, and voltage output strips according to an embodiment of the present invention;

FIG. 8 is a sectional side view of a PVC having a plurality of layers, each sensitive to a different wavelength of light and each having a different band gap energy to enhance collection of incident light, which is particularly suitable for use in a solar collector according to an embodiment of the present invention;

FIG. 9 is a graph of external quantum efficiency versus wavelength for a triple junction PVC;

FIG. 10 is a simplified schematic diagram showing a scheme for electrical connection of PVCs adapted to utilize different wavelengths of light according to an embodiment of the present invention;

FIG. 11A is a perspective view of an enclosure for a solar collector according to an embodiment of the present invention;

FIG. 11B is a side view of the enclosure of FIG. 11A according to an embodiment of the present invention;

FIG. 12 is a side view of an enclosure for a solar collector showing cooling vents according to an embodiment of the present invention;

FIG. 13 is a perspective view of an enclosure for a solar collector showing a heat exchanger for cooling substrates of the solar collector according to an embodiment of the present invention;

FIG. 14 is a side view of an alternative embodiment of a solar collector having a concentrator to increase efficiency showing the orientation of the substrates of the elevated-tiers relative to a base-layer, and the reflection of light among the plurality of substrates according to the present invention according the present invention;

FIG. 15 is a schematic perspective view of a solar collector with a plurality of substrates enclosed within an enclosure, the substrates having a PVCs formed thereon and oriented at angles relative to each other such that light reflected from a first substrate is reflected onto the surface of a second substrate according to an embodiment of the present invention;

FIG. 16 is a schematic side view of the substrates of the solar collector of FIG. 15 according to an embodiment of the present invention;

FIG. 17 is a simplified block diagram of substrates of a solar collector oriented at an angle relative to each other according to an embodiment of the present invention showing incident light reflecting from a surface of a first substrate on to a second substrate;

FIG. 18 is a simplified block diagram of substrates of a solar collector oriented at another angle relative to each other according to an embodiment of the present invention showing incident light reflecting from a surface of a first substrate on to a second substrate;

FIG. 19 is a simplified block diagram of substrates of a solar collector oriented at still another angle relative to each other according to an embodiment of the present invention showing incident light reflecting from a surface of a first substrate on to a second substrate;

FIG. 20 is a perspective view of a solar collector with three substrates shaped and oriented relative to one another to form inner surfaces of an inverted three sided pyramid according to an embodiment of the present invention;

FIG. 21A is a perspective view of a solar collector with four substrates shaped and oriented relative to one another to form inner surfaces of an inverted four sided pyramid according to an embodiment of the present invention;

FIG. 21B is a side view of the solar collector of FIG. 21A according to an embodiment of the present invention;

FIG. 21C is another perspective view of the solar collector of FIG. 21A showing incident light reflecting from substrate to substrate in the solar collector according to an embodiment of the present invention;

FIG. 21D is a top view of the solar collector of FIG. 21C showing incident light reflecting from substrate to substrate in the solar collector according to an embodiment of the present invention;

FIG. 21E is a plan view of a substrate of the solar collector of FIGs. 21A-21D showing PVCs thereon according to an embodiment of the present invention;

FIG. 22 is a perspective view of a solar collector with four substrates shaped and oriented relative to one another to form inner surfaces of an inverted four sided pyramid and further including a concentration lens according to another embodiment of the present invention;

FIG. 23A is a perspective view of a solar collector with a number of substrates shaped and oriented relative to one another to form inner surfaces of an inverted pentagon according to an embodiment of the present invention;

FIG. 23B is a top view of the solar collector of FIG. 23A according to an embodiment of the present invention;

FIG. 23C is a plan view of one side of the solar collector of FIGs. 23A-23B showing three substrates making up the side and the PVCs thereon according to an embodiment of the present invention;

FIG. 24 is a plan view of a substrate of a solar collector showing PVCs thereon according to an embodiment of the present invention;

FIG. 25 is a graph of external quantum efficiency of the PVCs on first and second substrates as a function of the angle relative to a normal, top or bottom surface of the solar collector; and

FIG. 26 is a normalized graph of external quantum efficiency and power of a single PVC on one of the first and second substrates as a function of the angle relative to a normal, top or bottom surface of the solar collector.

DETAILED DESCRIPTION

The present invention is directed to an improved solar collector having an array of substrates, each with at least one photovoltaic cell (PVC) formed on a surface thereof for converting light incident thereon into electrical energy.

A solar collector 100 according to the present invention will now be described with reference to FIGs. 3A and 3B. FIG. 3A is a plan view of a solar collector 100 including a number of wafers or substrates102, each with at least one PVC 104 formed on a surface 106 thereof for converting light incident thereon into electrical energy. The PVCs 104 can include a number of individual discrete PVCs formed on a single substrate 102, or a single monolithic PVC formed on a single substrate. Generally, the substrates 102 are enclosed within a reflective enclosure or an enclosure 108 according to an embodiment of the present invention. For purposes of clarity, many of the details of solar collectors 100 that are widely known and are not relevant to the present invention have been omitted. Referring to FIG. 3A, the substrates 102 of the solar collector 100 are ordered or arranged in a grid or an array 110 including a lower-tier or a base-layer 112 of substrates 102 electrically interconnected or coupled by a common ground conductor and/or common voltage outputs (not shown in this figure).

Preferably, the array 110 is a three-dimensional array including at least one elevated-tier 114 of substrates 102 positioned above and separated from the base-layer of substrates, such that at least a portion of the light passing between the substrates of the elevated-tier is absorbed by the substrates of the base-layer, thereby increasing the utilization of all light falling on the solar collector and improving its' overall efficiency. More preferably, referring to FIG. 3B, the enclosure 108 enclosing the array 110 of substrates 102, includes a top-wall 116 with an anti-reflective coating or surface 118 through which light is passed to the PVCs 104, and a bottom-wall 120 and sidewalls 122, 124, with reflective coatings or surfaces 126 to reflect light incident thereon back to the PVCs.

Generally, the enclosure 108 further comprises end-walls 128, 130, joining the top-wall 116 and bottom-wall 120. The end-walls 128, 130, also typically include anti-reflective coatings or surfaces 118, and join the top-wall 116 at an angle selected to facilitate passage of light to the PVCs 104 from a light source (not

shown) inclined relative to the surface of the top-wall. Preferably, each of the end-walls 128, 130, form an angle of from about 50 to about 75 degrees with the surface of the top-wall 116, and an angle of from about 105 to about 130 degrees with the bottom-wall 120. More preferably, the end-walls 128, 130, form an angle of about 60 degrees with the top-wall 116, and an angle of about 120 degrees with the bottom-wall 120. Angling of the end-walls 128, 130, is particularly desirable to enable a solar collector 100 located, installed or positioned in a substantially horizontal position to catch the rays of the rising or setting sun.

In one embodiment, shown in FIG. 3B, the elevated-tier 114 includes substrates 102 having surfaces 106 on which the PVCs 104 are formed oriented to receive light reflected from substrates of the base-layer 112. As also shown, the substrates 102 of the elevated-tier 114 can be suspended above the base-layer 112 by a support 132, such as a cord, strip, wire or wires, fastened or affixed to either the end-walls 128, 130, or sidewalls 122, 124, of the enclosure 108. Alternatively, the support 132 can be affixed to support pylons or structures (not shown) within the enclosure 108. Preferably, the support 132 is a ground-conductor134, for example a metal strip, wire or wires, to which each of the substrates 102 are electrically coupled. More preferably, the substrates 102 of the elevated-tier 114 are arranged in regularly spaced columns extending from end-wall 128 to end-wall 130 of the enclosure 108 and in rows extending from sidewall 122 to sidewall 124, and the support 132 includes a number of ground-conductors 134 extending between the end-walls to support each column of substrates. Generally, the ground-conductors 134 are joined and electrically coupled to a bus-bar or ground strip (not shown in these figures) bonded or otherwise affixed to an inner surface of the end-walls 128, 130.

In another embodiment, shown in FIGs. 4A and 4B, the solar collector 100 includes multiple elevated-tiers 114 including an upper or top elevated-tier 114A and a lower or bottom elevated-tier 114B. Each of the multiple elevated-tiers 114A, 114B, having upward facing substrates 102A on a top half or portion thereof and downward facing substrates 102B on a bottom half or portion thereof. The upward facing substrates 102A on the top portions are oriented to receive light directly through the top-wall 116 of the enclosure 108 and, in the case of the bottom elevated-tier 114B, also to receive light reflected from downward facing substrates 102B on the bottom portion of overlying top elevated-tier 114A. The downward

facing substrates 102B on the bottom portions of the elevated-tiers 114A, 114B, are oriented to receive either light reflected from upward facing substrates 102A on the top portion of an underlying elevated-tier, light reflected from the bottom-layer of substrates, or light reflected from the sidewalls 122, 124, and bottom-wall 120 of the enclosure 108. Preferably, the elevated-tiers 114A, 114B, are offset from one another such that at least some portion of the substrates 102 of each elevated-tier and of the bottom-layer 112 receive at least some light passed directly through the top-wall 116 of the enclosure 108.

FIG. 5 is a top view of a portion or column of an elevated-tier 114 of substrates 102 in a solar collector showing use of a pair of ground wires 136 to support and interconnect the substrates thereof according to an embodiment of the present invention.

FIG. 6 is a partial perspective view of the enclosure 108 showing a ground strip 138 attached, bonded or otherwise affixed to the inner surface of the end-walls 128, 130, and to which the air of ground wires 136 supporting the substrates 102 of the elevated-tiers 114 are physically and electrically coupled.

Generally, the substrates 102 of the base-layer 112 of the array are also arranged in columns and/or rows. For example, in one embodiment the substrates are arranged in a number of columns extending from end-wall 128 to end-wall 130 of the enclosure 108. FIG. 7 is a partial top view of such a column showing orientation of alternating pairs of substrates 102 along large flats of the 1,1,1, crystal face. FIG. 7 also shows interconnection of the substrates 102 by a common ground strip 140 and by voltage output strips or wires 142 electrically coupling the substrates together in parallel according to an embodiment of the present invention.

In yet another embodiment, the PVCs 104 include a number of different types of PVCs each sensitive to a different range of wavelengths of light and each having different band gap energy. Preferably, the PVCs 104 include at least two different types of PVCs selected from a group consisting of silicon based PVCs, gallium-arsenide (GaAs) based PVCs, aluminum-gallium-arsenide (AlGaAs) based PVCs, and germanium (Ge) based PVCs. More preferably, where the PVCs 104 include GaAs, AlGaAs or Ge based PVCs, which can be damaged by exposure to high levels of short wavelength or ultraviolet radiation, each substrate 102 has only a single type of PVC formed thereon, and the substrates having GaAs, AlGaAs or Ge based PVCs, are positioned and oriented within the array 110 to receive

substantially only light reflected from the sidewalls 122, 124, bottom-wall 120, or other substrates, such substrates of the base-layer 112 or upward facing substrates 102A on the top portion of an underlying elevated-tier 114. Because the reflected light is of lower overall intensity, and because certain wavelengths of light are completely or substantially absorbed by the surfaces which they first strike, the damaging radiation reflected onto the GaAs, AlGaAs or Ge based PVCs is reduced. Optionally, the GaAs, AlGaAs or Ge based PVCs 104 include a top passivation layer of oxide or nitride to filter out or remove damaging radiation further reducing the possibility or incidence of damage.

In still another embodiment, shown in FIG. 8, the PVCs 104 include monolithically grown devices having multiple layers or junctions, each sensitive to a different range of wavelengths of light and each having different band gap energy. FIG. 8 illustrates an example of a PVC 104 having a highly efficient triple junction cell structure. Referring to FIG. 8, a top gallium Indium-Phosphide (GaInP) layer absorbs short wavelength, high-energy photons, while successive gallium-arsenide (GaAs) and Ge layers absorb longer wavelength energy. As shown in the graph of FIG. 9, the total efficiency of the cell is thus greatly improved. FIG. 9 is a graph of external quantum efficiency versus wavelength for a triple junction PVC. It has been found that triple junction PVCs 104 can absorb photons in the range from 350 nanometers to 1800 nanometers, with an efficiency of greater than 87% of the total available solar spectral irradiance. Referring to FIG. 9, the external quantum efficiency of the GaInP layer is represented by the line identified by reference numeral 143; the external quantum efficiency of the GaAs layer is represented by the line identified by reference numeral 145; and the external quantum efficiency of the Ge layer is represented by the line identified by reference numeral 147. The line identified by reference numeral 149 represents the average Spectral irradiance in mW/cm^2.

FIG. 10 is a simplified schematic diagram showing a scheme for electrical connection of PVCs 104 adapted to utilize different wavelengths of light according to an embodiment of the present invention. Referring to FIG. 10, in a preferred embodiment each of the different types of PVCs 104, shown here as types 1, 2 and 3, are connected to a different DC to DC voltage converter or converter 144 within the enclosure 108 of the solar-collector 100. Each of the different types of PVCs 104 are connected in parallel to a single converter 144, and outputs of the converters

are connected in parallel to provide a common vdc output. The converters 144 raise or lower the voltage provided from the different types of PVCs 104 to match a voltage from another type of PVCs or of the common output voltage. The number of converters 144 in the solar-collector 100 depends on the number of different types of PVCs 104 contained therein, and generally is equal to or one less than the number of different types of PVCs. The value of the common output voltage can be chosen based power transport efficiency, requirements of external elements, such as batteries charged by the solar-collector or an inverter circuit for providing alternating current (AC) to a business or residence, or to match the output of one of the types of PVCs 104.

FIG. 11A is a perspective view of the enclosure 108 for the solar collector 100 according to an embodiment of the present invention. As shown the enclosure has a length (L) along the end-walls 128, 130, much greater than a width (WT, WB) associated with sidewalls 122, 124. The overall height (H) of the enclosure 108 is dependent on the number of elevated-tiers 114, the spacing therebetween, and size of a cooling mechanism (not shown in this figure) if any enclosed therein.

Preferably, the solar collector 100 is oriented so that the sun travels in an arc across the width of the enclosure 108, thereby maximizing the exposure of the substrates 102 with the PVCs 104 thereon to light passing through the end-walls 128, 130, when the sun is at a relatively low inclinations or elevations. For example, at or near sunrise and sunset. FIG. 11B is a side view of the enclosure 108 of FIG. 11A illustrating the angles with which the end-walls 128, 130, join the top-wall 116 and bottom-wall 120.

FIG. 12 is a side view of an enclosure 108 for the solar collector 100 showing a sidewall 122 having cooling vents 146 formed therein according to an embodiment of the present invention. Alternatively, the cooling vents 146 can be formed in the end-walls 128, 130, in the bottom-wall 120 or in a combination of the sidewalls 122, 134, end-walls, and bottom-wall. The cooling vents 146 enable heated air that would otherwise be trapped inside the enclosure 108 to escape. Preferably, both sidewalls 122, 124, have cooling vents 146 formed therein to enable air to circulate and pass through the enclosure 108. More preferably, the cooling vents 146 are sized, shaped and located to enable the substrates to be maintained at or below a semiconductor junction temperature of 125° F. This temperature is the maximum steady state temperature that can be tolerated by PVCs 104 formed on

silicon substrates without resulting in diffusion or migration of dopant materials out of the active layer, which can destroy or detrimentally effect the operation of the PVC.

In one version of this embodiment, the cooling mechanism includes, in addition to the cooling-vents 146, a number of fans 148, such as a box fan (only one of which is shown in phantom in FIG. 12), located inside the enclosure 108 to facilitate movement of air there through. Preferably, the fan 148 is electric and powered by at least portion of the output of one or more of the PVCs 104. The fan 148 may be directly wired to one or more PVCs 104 such that the output of the PVCs is solely dedicated to operating the fan, or the fan may be wired to draw off a portion of the output of the solar-collector 100. More preferably, the fan 148 draws power from the solar-collector 100 and is controlled by a thermostat (not shown) so that it is operated only as necessary to maintain the temperature in the enclosure 108 below a desired maximum temperature, thereby increasing efficiency of the solar-collector.

In another embodiment, the cooling mechanism consists of or further includes a heat exchanger 150 built into or thermally coupled to the bottom-wall 120 of the enclosure 108 for cooling substrates 102 of the solar-collector100. A perspective view of this embodiment is shown in FIG. 13. Referring to FIG. 13, the heat exchanger 150 generally includes one or more passages or tubes 152 through which a heat transfer fluid, such as a liquid or a gas, is passed to cool the solar-collector 100. In one preferred version of this embodiment, the heat transfer fluid is potable water that is circulated through a large tank or reservoir (not shown) located near the solar-collector 100 to provide heated water to a residence or business. Alternatively, the heat transfer fluid can be circulated through a second heat exchanger (not shown) over which air is forced to provide heat to the residence or business.

In yet another alternative embodiment, the solar collector 104 can further include a concentrator 154, such as a lens, to enhance collection of incident light, as shown in FIG. 14. In the embodiment shown in FIG. 14, the top-wall 116 includes or has been replaced by a Fresnel lens to focus or concentrate incident light onto substrates 102 of the base-layer 112. A Fresnel is a lens having a surface of stepped concentric circles, resulting in a shape that is thinner and flatter than a conventional parabolic lens of equivalent focal length.

In still another alternative embodiment, the surfaces of PVCs 104 of the elevated-tiers 114 are positioned and oriented at an angle relative to the surface of PVCs of the base-layer 112 to produce multiple reflections of light reflected from the base layer. In the example shown in FIG. 14 light reflected from the base layer 112 is reflected to surfaces of PVCs 104A in a first elevated-tier 114A positioned at an acute angle thereto, and from the first elevated-tier to other PVCs with the same tier or to PVCs 104B in a second elevated tier 114B. This embodiment has the advantages of enabling substantially all of the light reflecting from the base-layer 112 to be reflected to the elevated-tiers 114 and be absorbed without providing a reflective surface on the enclosure.

In a preferred version of the above embodiment, the types of PVCs 104 in the base-layer 112 and elevated-tiers 114 include multiple layer or junction devices, such as the triple junction PVC 104 shown in FIG. 8 above. More preferably, the PVCs 104 in the elevated-tiers 114 include GaAs, AlGaAs, Ge or Si based PVCs, and are positioned and oriented to receive substantially only reflected light. As explained above, GaAs, AlGaAs, Ge or Si based PVCs have high efficiencies at longer wavelengths, but can be damaged by exposure to high levels of short wavelength or ultraviolet radiation. Because the reflected light is of lower overall intensity, and because certain wavelengths of light are completely or substantially absorbed by the PVCs 104 which they first strike, the damaging radiation reflected onto the GaAs, AlGaAs, Ge or Si based PVCs is significantly reduced.

In yet another aspect of the present invention embodiment, a solar collector is provided having an array of substrates with photovoltaic cells, the substrates oriented at angles relative to each other such that light reflected from a first substrate is reflected onto the surface of a second substrate, thereby improving efficiency of the solar collector.

A solar collector 200 according to this aspect of the present invention will now be described with reference to FIGs. 15 to 26. For purposes of clarity, many of

the details of solar collectors 200 that are widely known and are not relevant to the present invention have been omitted. FIG. 15 is a is a schematic perspective view of a solar collector 200 including a number of wafers or substrates 202A, 202B, enclosed within an enclosure 206 and each of the substrates including at least one PVC 208 formed on a top surface 210 thereof for converting light incident thereon into electrical energy. External electrical connection to the PVCs 208 is through a ground-conductor 212 electrically coupled, epoxied (with an electrically conductive epoxy) or soldered to the substrates 202A, 202B, and positive-conductors 214, 216, electrically coupled or soldered to each of the PVCs. The PVCs 208 on the different substrates 202A, 202B, can be electrically connected in series or in parallel depending on the voltage or current produced by the PVCs and voltage or current required or desired out of the solar collector 200.

In accordance with the present invention, the substrates 202A, 202B, are arranged in a three-dimensional array 218 having at least first and second substrates 202A, 202B, oriented at an angle relative to each other, such that at least a portion of the light reflected from the first substrate 202 is reflected onto the second substrate 202B and absorbed, thereby increasing the utilization of all light falling on the solar collector and improving its' overall efficiency. Preferably, both the first and the second substrates 202A, 202B, receive light thereon, and are oriented with respect to each other and to a direction of propagation of light incident on the solar collector 200 such that light reflected from either substrate is reflected onto the other substrate. More preferably, referring to FIG. 16, the angle α between the surfaces of the first and second substrates is between about 140° and a predetermined minimum angle greater than or equal to about 20°. Alternatively expressed, the first and the

second substrates 202A, 202B, are oriented relative to a normal or to a top surface of the solar collector 200 to form angles θ of between about 20° and about 70°.

To maximize the incident light reflected between the substrates 202A, 202B, the substrates are positioned such that the edges nearest or forming the apex of the angle α, are proximal to each other and to the apex of the angle. Preferably, the edges of the substrates 202A, 202B, are abutting or adjoining.

The substrates 202A, 202B, of the array 218 can be held in position above the base of the solar collector by a support (not shown), such as a cord, strip, wire or wires, or stamped metal plate(s) fastened or affixed to the sidewalls of the enclosure 206. Alternatively, the substrates 202A, 202B, can be held in position by support pylons or structures (not shown) below the substrates within the enclosure 206.

The PVCs 208 can include a number of individual discrete PVCs formed on a single substrate, as shown on substrate 202A, or a single monolithic PVC formed on a single substrate, as shown on substrate 202B. The PVCs 208 can include a number of different types of PVCs each sensitive to a different range of wavelengths of light and each having different band gap energy. For example, the PVCs 208 include PVCs selected from a group consisting of silicon based PVCs, gallium-arsenide (GaAs) based PVCs, aluminum-gallium-arsenide (AlGaAs) based PVCs, and germanium (Ge) based PVCs. Preferably, the PVCs 208 include monolithically grown devices having multiple layers or junctions, each sensitive to a different range of wavelengths of light and each having different band gap energy. One example of such a multiple-junction PVC is a triple junction PVC (not shown) that has a top gallium Indium-Phosphide (GaInP) layer to absorb short wavelength, high-energy photons, while successive gallium-arsenide (GaAs) and Ge layers absorb longer

wavelength, low-energy photons. Such PVCs are commercially available, for example, from Spectrolab Inc. of Sylmar, California.

Generally, the substrates 202A, 202B, are mounted on cooling plates 220, if required.. A heat exchanger 222 is built into or thermally coupled to the cooling plates 220 of the enclosure 206 for cooling substrates 202A, 202B, of the solar-collector 200. Preferably, the temperature and flow rate of a cooling fluid passed through the heat exchanger 222 is selected to enable the substrates to be maintained at or below a semiconductor junction temperature of 125° F. This temperature is the maximum steady state temperature that can be tolerated by PVCs 208 formed on silicon substrates without resulting in diffusion or migration of dopant materials out of the active layer, which can destroy or detrimentally effect the operation of the PVC.

The cooling plates 220 and the heat exchanger 222 can be made on any suitable metallic, ceramic or polymeric material having the necessary structural stability, and heat transfer characteristics. Optionally, the cooling plates 220 are made of an electrically conductive material and are electrically as well as thermally coupled to the substrates 202A, 202B, and the ground-conductor 212 is electrically coupled to the substrates through the cooling plates.

In one embodiment, the enclosure 206 enclosing the array 218 of substrates 202A, 202B, is a reflective enclosure including a top-wall 224 with an anti-reflective coating or surface (not shown) on a top surface thereof through which light is passed to the PVCs 208, and a bottom-wall 228 and sidewalls 230, 232, 234, 236, with reflective coatings or surfaces (not shown) to reflect light incident thereon back to the PVCs. The top-wall 224 can also include a reflective coating or surface on a lower surface thereof to redirect light reflected from the substrates 202A, 202B,

or the bottom-wall 228 back on to the PVCs 208. Although not shown, the sidewalls 230, 232, 234, 236, can join the top-wall 224 at an angle selected to reflect light back to the substrates 202A, 202B. Angling of the sidewalls 230, 232, 234, 236, is particularly desirable to enable a solar collector 200 located, installed or positioned in a substantially horizontal position, such as to catch the rays of the rising or setting sun.

A number of embodiments of a solar collector 200 according to the present invention having substrates of oriented at various angles α with respect to one another will now be described with reference to FIGs. 17, 18 and 19. FIGs. 17, 18 and 19 are tracing models depicting reflections from one surface to the other. For clarity only light incident on one surface and reflected to the other is shown. It will be appreciated that since both substrates 202A, 202B, are oriented at equal angles with respect to the direction of the incident light rays, the light incident on the other surface and reflected therefrom will be the mirror image of that shown.

Referring to FIG. 17 there is shown a simplified block diagram of substrates 202A, 202B, of the solar collector 200 oriented at an angle of 120° relative to each other or 30° relative to the bottom-wall 228 of the solar collector. In this embodiment, it appears there is little reflection of light from substrate 202A to substrate 202B. However, it should be noted that not all light rays incident on the first substrate 202A are parallel or normal to the top of the solar collector 200. Rather, some light rays will strike the first substrate 202A at a more oblique angle and be reflected onto the second substrate 202B. The light reflected onto the second substrate 202B, is absorbed by the PVCs 208 and converted into electrical energy, thereby increasing the external quantum efficiency of the solar cell 200.

FIG. 18 illustrates the substrates 202A, 202B, oriented an angle of 90° relative to each other or 45° relative to the bottom-wall 228 of the solar collector and the incident light rays. When compared with the ray tracing of FIG. 17, this model illustrates the increase in the intensity of light reflected between the substrates 202A, 202B, for decreasing angles between the substrates.

FIG. 19 illustrates the substrates 202A, 202B, oriented an angle of 40° relative to each other or 70° relative to the bottom-wall 228 of the solar collector and to the normal or top of the solar collector 200. When compared with the ray tracing of FIGs. 17 and 18, this model further illustrates the increase in the intensity of light reflected between the substrates 202A, 202B, for decreasing angles between the substrates. This model also illustrates the occurrence of tertiary reflections in which light reflected to the second substrate 202B and not absorbed thereby is reflected back to the first substrate 202A where it can be absorbed, thereby further increasing the external quantum efficiency of the solar cell 200. Although not illustrated in the preceding figure, it will be appreciated that tertiary or higher order reflections can occur between any two substrates 202A, 202B, and more particularly by those separated by angles of 45° or less.

In yet another embodiment, illustrated in FIGs. 20 to 23C, the solar collector 200 can include a plurality of three or more substrates are shaped and oriented relative to one another such that the surfaces of the substrates form at least part of a concave inner surface of a polyhedron.

For example, in FIG. 20 there is shown an array 218 of three substrates 202A, 202B, 202C, shaped and oriented relative to one another to form at least part of first, second and third inner surfaces of an inverted three sided pyramid 242. In the embodiment shown, because the three substrates 202A, 202B, 202C making up

the pyramid 242 are equilateral triangles, the angle α separating any two adjoining substrates is 60°. However, it will be appreciated that each substrate 202A, 202B, 202C can further be sized and shaped to form angles θ of between about 20° and about 70° relative to the bottom-wall 228 or top-wall 226 of the enclosure 206 or to the normal of the solar collector 200. Moreover, although shown as a pyramid 242 with equilateral sides this need not be the case in all embodiments. For example, in applications where the solar collector 200 must be mounted such that light will predominantly enter at an oblique angle to the normal surface of the solar collector, it may be desirable that the substrate 202A making up the side of the pyramid 242 receiving the most direct incident light be larger than the other two substrates 202B, 202C.

In another embodiment, illustrated in FIGs. 21A through 21E, the solar collector 200 can include four substrates 202A, 202B, 202C, 202D shaped and oriented relative to one another to form at least part of first, second, third and fourth inner surfaces of an inverted four sided pyramid 246. In the embodiment shown, because the four substrates 202A, 202B, 202C, 202D, making up the pyramid 244 are equilateral triangles, the angle α separating any two adjoining substrates is 90°. However, as noted above each substrate 202A, 202B, 202C, 202D, can further be sized and shaped to form angles θ of between about 20° and about 70° relative to the bottom-wall 228 and top-wall 226 of the enclosure 206 or to the normal of the solar collector 200.

FIG. 21C is another perspective view of the solar collector 200 of FIG. 21A showing an incident light ray 201 reflecting from substrate to substrate in the solar collector 200. In this embodiment, it appears the substrates 202A, 202B, 202C, 202D, oriented an angle of 90° relative to each other or 45° or larger relative to the

bottom-wall 228 of the solar collector 200. This model also illustrates the occurrence of secondary, tertiary and higher order reflections which further increase the external quantum efficiency of the solar cell 200.

FIG. 21D is a top view of the solar collector 200 of FIG. 21C showing the incident light ray 201 reflecting from substrate 202 to other substrates in the solar collector.

FIG. 21E is a plan view of a substrate 202 of the solar collector of FIGs. 21A-21D showing one or more PVCs 208 thereon, and a schematic representation of the electrical connections thereto. Although shown as a single monolithic PVC 208, it will be appreciated that the substrate 202 can include any number of PVCs sized and shaped as desired to conform to the substrate. For example, the substrate 202 can include two identical PVCs 208 having a right triangular shape and adjoining along one leg thereof. Also, it will be appreciated that where the substrate 202 includes multiple PVCs 208, the PVCs can be electrically connected in parallel or in series with one another, as well as with PVCs on other substrates, depending either on the voltage and/or current produced or required.

FIG. 22 is a perspective view of another embodiment of the solar collector 200 with four substrates 202A, 202B, 202C, 202D, shaped and oriented relative to one another to form inner surfaces of an inverted four sided pyramid 246 and further including a concentration lens or concentrator 248 through which light is passed to at least the first substrate 202A. Preferably, the concentrator 248 is a lens, such as a one or two-sided convex or concave lens or a Fresnel lens, adapted to enhance or concentrate collection of incident light on one or substrate or substrates. More preferably, the concentrator 248 is a non-imaging concentrator that diffusely or non-diffusely focuses and/or concentrates light on the substrates 202.

FIG. 23A is a perspective view of yet another embodiment of the solar collector 200 with a number of substrates 202A, 202B, 202C, 202D, 202E, 202F shaped and oriented relative to one another to form inner surfaces of a polyhedron having a pentagon or pentagonal cross-section (hereinafter pentagon 250). Preferably, the substrates 202A, 202B, 202C, 202D, 202E, are angled relative to one another and to the bottom-wall 228 of the solar collector 200 to form an inverted pentagon 250 having a cross-sectional area that decreases from top to bottom. FIG. 23B is a top view of the solar collector 200 of FIG. 23A. Each substrate 202A, 202B, 202C, 202D, 202E, making up a side of the pentagon 250 is sized and shaped with respect to each other and to a direction of propagation of light incident on the solar collector 200 such that light reflected from one substrate is reflected onto a substrate making up another side of the pentagon. Preferably, the angle α between the surfaces of the substrates 202A, 202B, 202C, 202D, 202E, is between about 60° and about 80°. More preferably, each substrate 202A, 202B, 202C, 202D, 202E, making up a side of the pentagon 250 is further sized and shaped to form angles θ of between about 20° and about 70° relative to the bottom-wall 228 or top-wall 226 of the enclosure 206 or to the normal of the solar collector 200. Moreover, although shown as a pentagon 250 with equilateral sides this need not be the case in all embodiments.

FIG. 23C is a plan view of one side of the solar collector 200 of FIGs. 23A-23B showing three PVCs 208 or making up one substrate or side of the inverted pentagon 250. Although shown as a single substrate 202A having three PVCs 208 formed thereon, it will be appreciated that each side of the pentagon 250 can also be made up of a number of discrete substrates, for example three substrates, each having one or more PVCs 208 thereon.

In one version of this embodiment, the solar collector 200 can have an inverted pentagon 250 further including a concentrator 248 as described above in connection with FIG. 22.

Finally, although described using the examples of three and four sided inverted pyramids, and an inverted pentagon, it will be appreciated that that the array 218 can include any number of substrates 202 sized, shaped and oriented to form any geometric figure or shape formed by planar surfaces that also form angles θ of between about 20° and about 70° relative to the bottom-wall 228 and top-wall 224 of the enclosure 206 or to the normal of the solar collector 200.

EXAMPLES

The following examples made with reference to FIGs. 24 through 26 illustrate advantages of the solar collector 200 according to the present invention for a more efficient conversion of the available photons or light into electrical energy. The examples are provided to illustrate certain embodiments of the present invention, and are not intended to limit the scope of the invention in any way.

In this examples, the solar collector 200 included first and second substrates 202A, 202B, sized, shaped and positioned substantially as shown in FIGs. 15 and 16, and angled with respect to each other at various angles including those shown in FIGs. 17 to 19. Each substrate 202A, 202B, included two triangular PVCs 208A, 208B, positioned as shown in FIG. 24. The substrates 202A, 202B, were electrically connected such that the power and efficiency of each could be measured both independently and in combination with the other.

FIG. 25 illustrates the results from a main experiment or example with the efficiency as a function of an angle θ relative to the normal or to a top surface of the solar collector 200 of bottom wall 228 for two different PVCs 208A on the first and

second substrates 202A, 202B. As shown by line labeled reference number 252, the efficiency shows a gradual increase of from about 26.2% to about 35% for increasing angles θ of from 0° to about 70° relative to the normal or to the top or bottom surface 224, 228, of the solar collector 200. The average increase in the efficiency is more than 9.4%.

FIG. 26 illustrates the increase in both normalized power and efficiency as a function of an angle θ relative to the normal or to the top or bottom surface 224, 228, of the solar collector 200. In this experiment, light to emphasize the increase power and efficiency due to reflected light, incident light was shown on substrate 202A only, and blocked from substrate 202B. This figure to shows that the power and efficiency increases rapidly for both substrates 202, 202B, in the angular range shown between the dashed lines as a result of absorbing most of the reflected light after one reflection. The increase in power and efficiency for substrate 202A, indicated by line labeled reference number 256, is accounted for by secondary, tertiary or higher order reflections back from the second substrate 202B back to the first substrate. The increase in power and efficiency for substrate 202B is indicated by line labeled reference number 254. Referring to FIG. 26, it is seen that a first onset of rapid increase in power and efficiency is evident above angles of about 33° as a result of reflections. Above 60°, the second onset of rapid increase in power and efficiency is evident as a result of reflections. Both the efficiency and power increase with increasing angle.

It believed that the efficiency increases as a function of an increase in angle while the power decreases. Although, this seems contradictory as the efficiency is dependent on the power from by the expression:

$$Eff=P_{out}/P_{in} \quad (1)$$

where P_{out} is the power output of the solar collector 200 and P_{in} is the power incident on the solar collector, which in the above examples is about 1000 W/m2.

Another way to calculate the efficiency of the solar collector 200 is by the expression:

$$Eff = I_{sc}V_{sc}FF/(\text{Sun's Irradiance})(\text{Area}) \qquad (2)$$

where I_{sc} is the current out of the solar collector 200; V_{sc} is the voltage out of the solar collector, FF is the fill factor, and Sun's Irradiance is the Sun's Irradiance or power in W/m^2 and area is the area of the solar collector. As is known in the art, the fill factor on an I-V (current-voltage) curve characterizing the output of a solar cell or module, the ratio of the maximum power to the product of the open-circuit voltage and the short-circuit current. The higher the fill factor (FF) the "squarer" the shape of the I-V curve.

Hence, from Eq. (1), it would appear that as the power decreases, so should the efficiency. However, referring to Eq. (2) it is seen that because the product of $I_{sc}V_{sc}FF$ decreases at a slower rate than the cosine of the angle of the substrates of the solar collector, and because the irradiance of the simulated solar light is constant, the efficiency actually increases when as the value in the numerator at a particular angle is divided by the smaller number from the cosine of the area of that angle.

The foregoing description of specific embodiments and examples of the invention have been presented for the purpose of illustration and description, and although the invention has been illustrated by certain of the preceding examples, it is not to be construed as being limited thereby. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, and obviously many modifications, embodiments, and variations are possible in light of the above

teaching. It is intended that the scope of the invention encompass the generic area as herein disclosed, and by the claims appended hereto and their equivalents.